AN INVESTIGATION OF THE EARLY STAGES OF FRETTING

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by

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ABSTRACT

Title: AN INVESTIGATION OF THE EARLY STAGES OF FRETTING

Author: William F. Tighe, Jr., Lieutenant, U.S. Coast Guard

Submitted to the Department of Naval Architecture and Marine Engineering on May 22, 1954 in partial fulfillment of the requirements for the degree of Naval Engineer.

The primary purpose of this investigation was to determine the shape of the initial portion of the curve of fretting weight loss versus the number of cycles run. Pervious work in the field has shown this curve to be concave downward over the initial portion. It has been proposed that the curve is actually concave upward over this portion, due to the fact that the abrasive action is presumably more violent than the shearing action. The conditions under which the tests were conducted, were chosen such that it was anticipated that the specimen weight loss would be relatively large over a short interval of time. The tests of mild steel specimens fretted against mild steel specimens were conducted under these conditions, varying the duration of test from 1 to 10,000 cycles.

The results of this investigation showed that the curve in question actually had a point of inflection in the portion under investigation. At the origin, the curve was concave downward followed by a turn to concave upward. This result not only substantiated the initial proposal but also added some additional information which was not anticipated.

It is recommended that these tests be repeated in dry air as well as other atmospheres to establish definite quantitative results. It is also recommended that the frequency of alternation be lowered to as small a value as possible in order to increase the specimen weight loss in a given interval of time.

The second purpose of the investigation was to establish a relationship between specimen weight loss and some physical measurement of fretting damage. To this end, the area of damage as well as its depth was measured and plotted against specimen weight loss.

The result of this series of investigations showed that any attempt to use the area of damage as a substitute for weight loss is impractical. It appears to be quite possible to use the depth of damage as a measure of fretting damage. The relationship obtained between specimen weight loss and the depth of fretting damage can be considered qualitative only due to a lack of sufficient data. The depth of damage, however, definitely increases as the weight loss increases. It is recommended that additional tests be made to firmly establish the quantitative relationship between specimen weight loss and the depth of fretting damage.

Thesis Supervisor: I-Ming Feng, Ph.D.
Title: Assistant Professor of Mechanical Engineering

Cambridge, Massachusetts
May 22, 1954

Secretary of the Faculty
Massachusetts Institute of Technology
Cambridge, Massachusetts

Dear Sir:

In accordance with the requirements for the Degree of Naval Engineer, I submit herewith a thesis entitled, "An Investigation of the Early Stages of Fretting."

Respectfully,

William F. Tighe, Jr.
Lieutenant
U. S. Coast Guard

ACKNOWLEDGEMENTS

The author wishes to express his sincere thanks and appreciation to Professor I-Ming Feng for his advice and encouragement during this investigation. Appreciation is also extended to Mr. J. Purdy for his help in setting up the testing equipment.

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I INTRODUCTION

Fretting is a type of damage that occurs at the interface of two loaded surfaces that are in contact and subject to relative slip. Fretting often appears on surfaces intended to have no relative motion but which are associated with vibrating machinery. It may occur, for example, on the mating surfaces of a bearing race and of a shaft tightly fitted together. It has been shown that some slippage, no matter how small, is necessary to cause fretting. In the absence of slip there is no fretting (3, 8).

Fretting damage is a continual source of uncertainty in the operation of all machinery subject to vibration, as it quickly destroys close tolerences and increases the susceptibility to fatigue (4). Examples of fretting damage are often found in variable-pitch propellers, connecting rods, knuckle pins, ball and roller bearings, clamped and bolted flanges, pins in gear trains, suspension springs, electrical contacts, and splined surfaces. This type of damage is particularly serious in the airplane and automotive industries where close fits are employed on equipment subject to vibration. In order to eliminate or mitigate the damage caused by fretting, a better understanding of the subject is essential. The purpose of the present investigation is to add to the understanding of the subject of fretting and the means of investigating fretting damage.

The majority of the work done to date in the field of fretting has dealt with the mechanism of fretting and some of its qualitative aspects. Feng (2, 9, 10) has analysed the basic factors of metal transfer and wear. The mechanism of wear, as proposed by Feng, is caused by a pair of actually contacting high spots. When these contacting high spots support a normal load that is large enough to cause plastic deformation of the metal, the deformation will cause a roughening of the interface. This roughening of the interface produces a mechanical interlocking which strengthens the interface in resisting a tangential force. Thus the application of a tangential force will cause the peak of one of the pair of high spots to shear off instead of separating the contacting high spots at the original interface. This sheared peak may either become a loose wear particle or remain attached, depending upon the factors operating to cause it to adhere to the adjacent high spot. Feng and Rightmire (1) have applied this theory to explain the mechanism of fretting, and have shown mechanical wear to be the primary cause of fretting damage.

The wear particles formed by the shearing off of the peaks of the contacting high spots form hard oxides which cause abrasive wear. A number of investigations (1, 3, 8, 10) have been made in different atmospheres to determine the effect of oxides on fretting damage. These investigations have shown that oxidation, while having a very marked effect, is only a secondary cause of fretting.

In addition to the investigations of the effect of atmospheres, investigations have been made of some of the other factors affecting fretting damage. Tests conducted by Feng and Uhlig (8) have shown that a decrease in fretting damage is caused by an increase in relative humidity, temperature and frequency of alternation; and an increase in fretting damage is caused by an increase in the number of cycles run, relative slip and normal load. Parts of these tests have also been corroborated by previous investigators (1,3). In addition, fretting damage appears to be greater, other things being equal, the better the original fit of the mating surfaces (6).

Several investigations have been made of fretting damage using various metals and nonmetals fretted against themselves and against each other. Godfrey (7) used platinum, glass, quartz, ruby, mica, and chrome-alloy steel. He found that the tendency for fretting depended upon the surface hardness of the metal tested. He also found that the introduction of a lubricant between the surfaces of the materials decreased the amount of fretting damage done in all cases, but that it was not eliminated. This latter fact was also borne out in the investigations of Tomlinson, Thorpe and Gough (3).

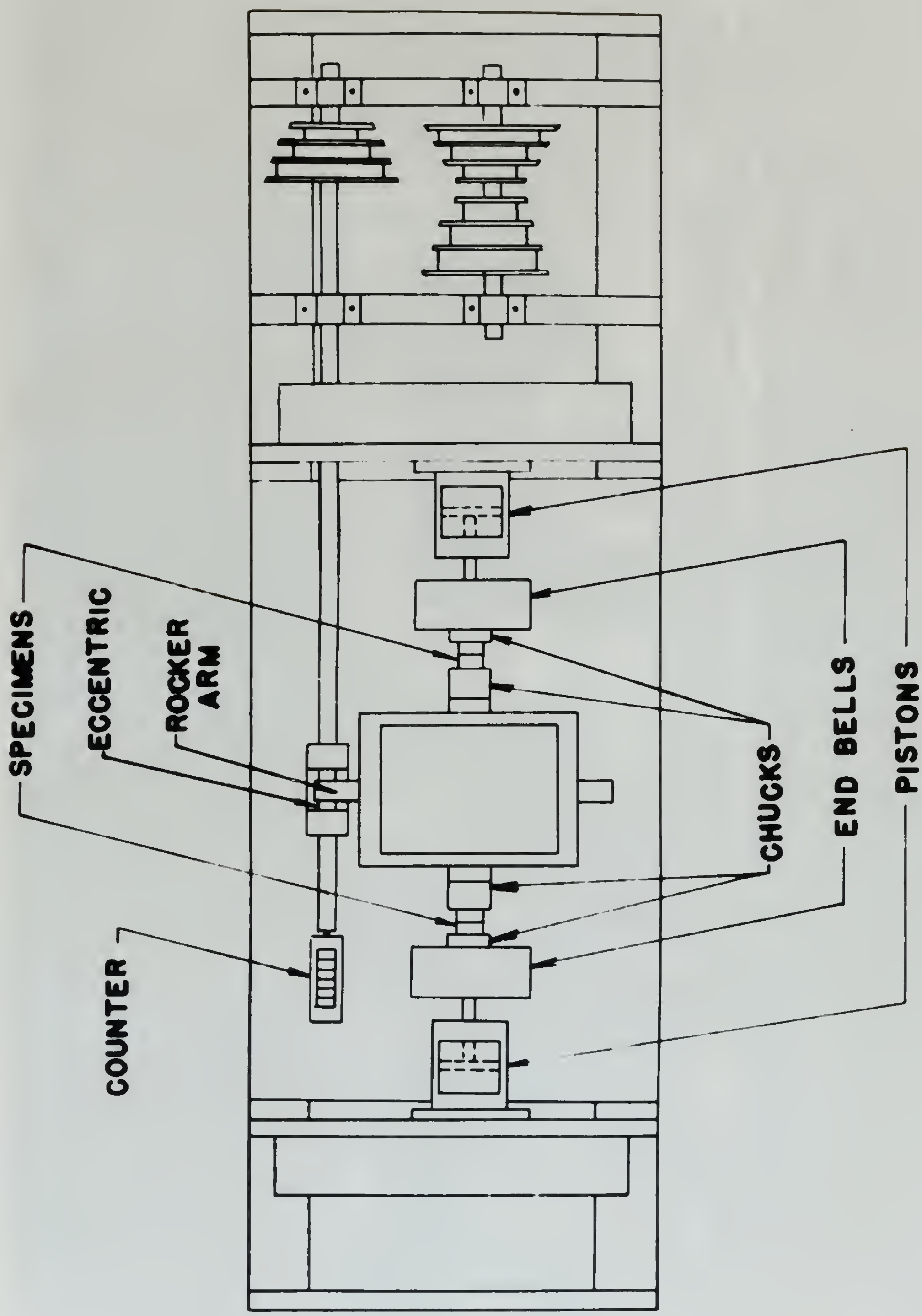
References (1) and (8) both present the results of mild steel specimens fretted against mild steel specimens in dry air. These results are presented in the form of curves of Specimen Weight Loss versus Number of Cycles Run. Both of these curves are concave downward at the origin, i.e., during the shifting period from shearing

action to abrasive wear. Feng and Rightmire (1) have proposed that this curve is actually concave upward during the shifting period. This proposal is based on the fact that the rate of wear probably increases during the shifting period as the abrasive action is presumably more violent than the shearing action. This proposal seems to be supported by the points plotted in Figures 5 and 6 of the investigation by Wright (11). One of the purposes of the present investigation is to substantiate this proposal by decreasing the number of cycles run and increasing the amount of fretting that occurs by decreasing the frequency of alternation. This will tend to expand the initial portion of the curve. The test apparatus shown in Figures I, II, and III and described in Appendix A was used for the investigation.

Using weight loss as a measure of fretting damage is not always the best means, even though it can be measured quantitatively and relatively accurately. An excellant example is the case in which two clean surfaces are fretted against each other in a vacuum. Because of the adhesion between clean metallic surfaces in a vacuum, the peak sheared from one high spot sticks to the opponent high spot and becomes a piece of transferred metal. Thus very little loose wear material can be produced, metal merely being transferred back and forth from one specimen to another. If the specimens are made of the same material, the weight loss of each is practically nil.

Nevertheless, both specimens are subject to serious damage caused by metal transfer.[1] A second purpose of this investigation is to try and establish a technique for measuring the damage in such cases by correlating weight loss and some physical measure of fretting damage. An attempt will be made to find some relationship between specimen weight loss and either the depth or the area of damage or both.

[1] Feng, I. Ming, and Rightmire, B.G., "The Mechanism of Fretting", Lubrication Engineering, Vol. 9, No. 3, 1953, p. 135.



SCHEMATIC OF TEST MACHINE

FIGURE I

FIGURE II
Top view of test apparatus

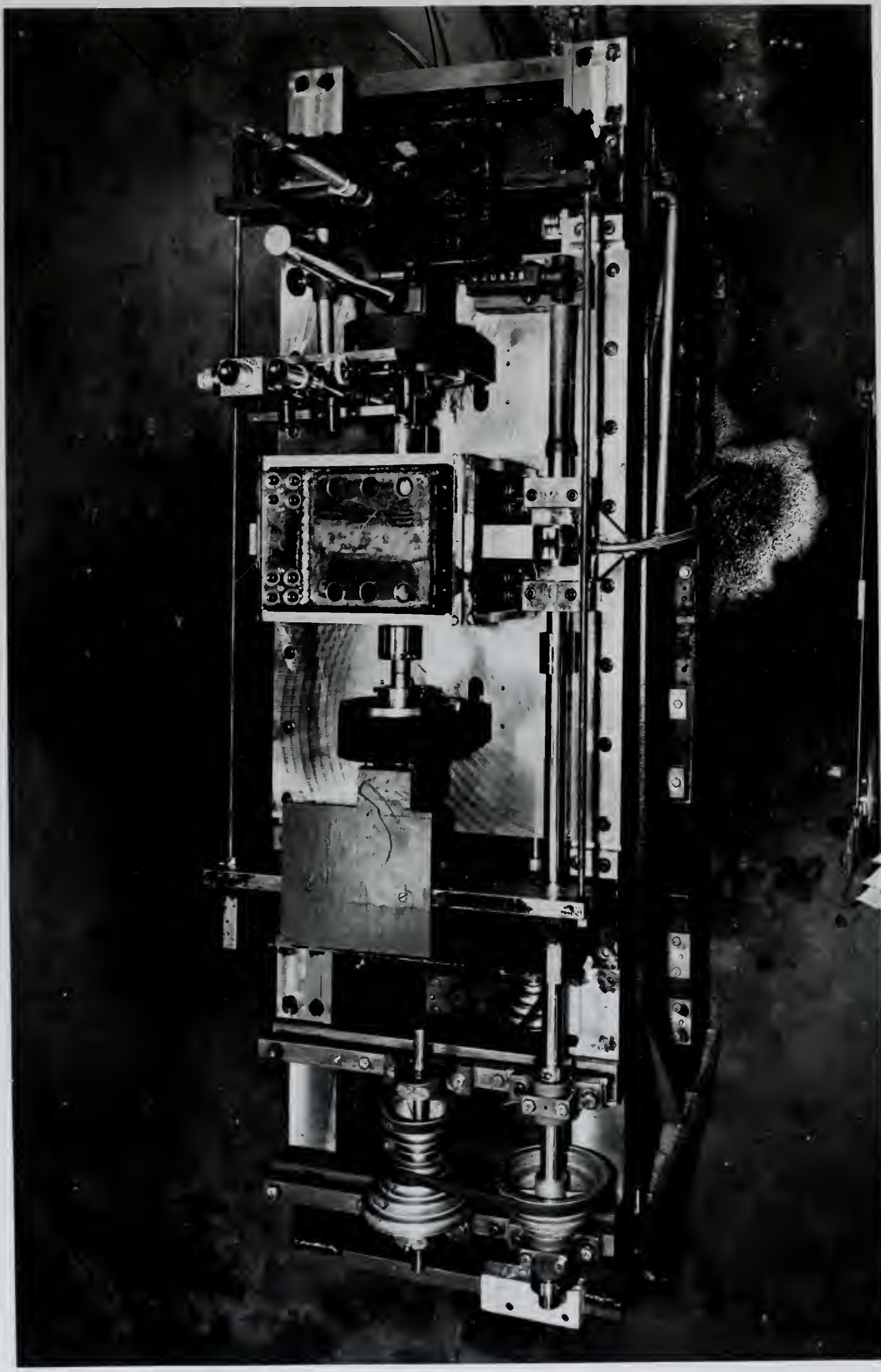


FIGURE III
Side view of test apparatus

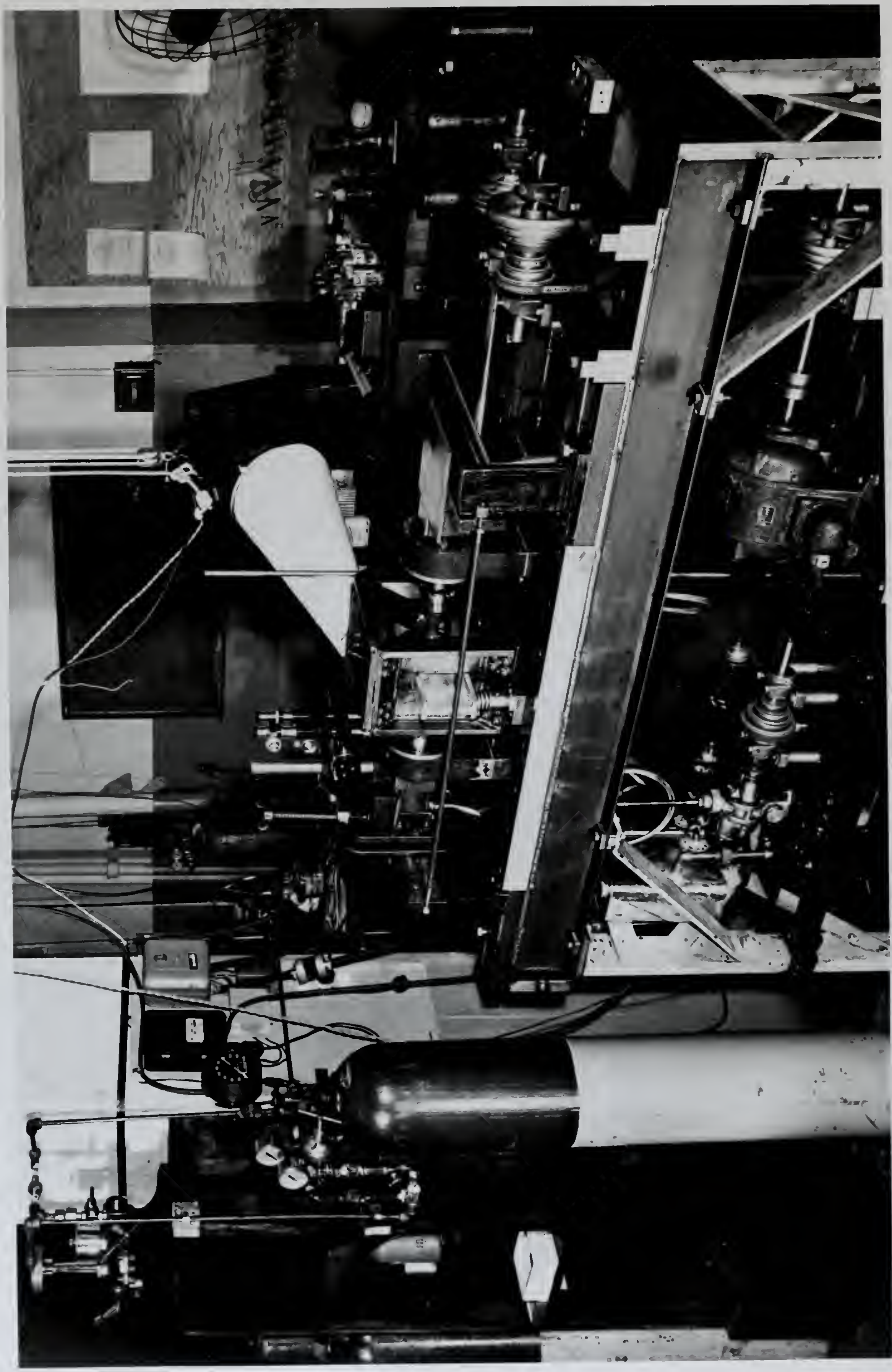
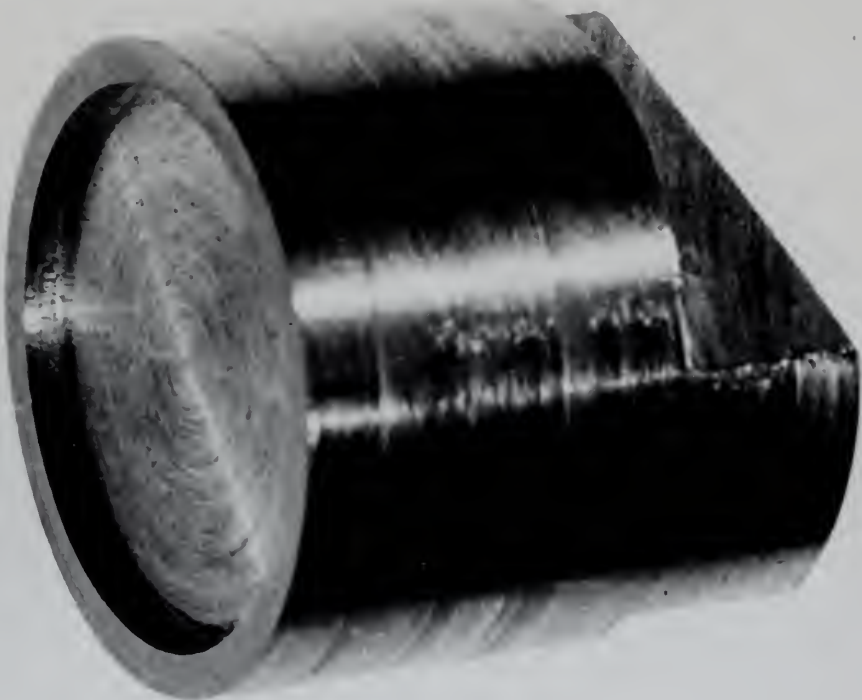


FIGURE IV

Standard test specimen



II PROCEDURE

The specimens to be tested were prepared as outlined in Appendix B, mounted in the test machine and the tests made. All of the tests were made under a standard set of test conditions in an atmosphere of dry air at room temperature. The standard normal loading was 5300 psi. The relative slip was maintained at 0.0036 inch, and the frequency of alternation was kept constant at 79 cycles per minute.

Several tests were first made to determine an appropriate number of cycles at which the fretting damage was such that it was fairly easy to identify individual pits. Two runs were then made, one for five cycles duration and one for ten cycles duration. A number of individual pits were selected from each specimen and a measurement made of each pit area and its depth. This procedure was followed in order to find a relationship between pit area and depth indicating pit growth. It was anticipated that this might lead to a relationship that could be corrolated with specimen weight loss.

Several tests were then made varying the duration of test from 10 to 300 cycles. The specimens were pickled once and weighed upon the completion of each test. The recorded specimen weight loss was an average of the weight losses for the four specimens tested. A representative specimen from each of six tests was selected, and

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Several tests were first made to determine an appropriate number of cycles at which the fretting damage was such that it was fairly easy to identify individual pits. Two runs were then made, one for five cycles duration and one for ten cycles duration. A number of individual pits were selected from each specimen and a measurement made of each pit area and its depth. This procedure was followed in order to find a relationship between pit area and depth indicating pit growth. It was anticipated that this might lead to a relationship that could be correlated with specimen weight loss.

Several tests were then made varying the duration of test from 10 to 300 cycles. The specimens were pickled once and weighed upon the completion of each test. The recorded specimen weight loss was an average of the weight losses for the four specimens tested. A representative specimen from each of six tests was selected, and

a measurement was made of the total area of fretting damage and the greatest depth of damage. The purpose of this series of tests was to find the shape of the curve of specimen weight loss versus the number of cycles run. In addition to this, the tests were an attempt to find a relationship between total area and depth of damage and to corrolate this with specimen weight loss.

A series of tests was made varying the duration of test from 1 to 10,000 cycles. The specimens were cleaned and weighed after test, then pickled and reweighed. This was followed by a second pickling and reweighing. One or two specimens from each test were selected and a measurement made of the deepest depth of fretting damage. The purpose of this series of tests was three fold. First it was an attempt to determine the fretting weight loss curve. Secondly it was felt that this procedure would lead to a relationship between specimen weight loss and depth of damage. Thirdly it was an attempt to determine what effect a first and second pickling procedure would have upon specimen weight loss.

III RESULTS

The results of the investigation are presented in Tables I, II, and III, and in figures V, VI, VII, and VIII. Significant points to be noted are as follows:

1. Initially the area of an individual pit increases faster than the depth. The depth then begins to increase faster than the area, followed by the area again increasing faster than the depth.

2. Initially the rate of specimen weight loss is high and soon reaches a steady state. Shortly after this steady state is reached, the rate of weight loss again increases markedly and settles at a new steady state value.

3. The specimen weight loss due to both first and second pickling is not a constant, but is a function of the amount of damage caused by fretting.

4. The total area of fretting damage is essentially a constant over the range from 30 to 300 cycles.

5. The specimen weight loss increases with an increase in the depth of fretting damage.

TABLE I

INDIVIDUAL PIT MEASUREMENT DATA

Normal Load - 5300 psi
Slip - 0.0036 in.

Medium - dry air

Pit	Duration of Test(cycles)	Frequency of Test (cpm)	Pit Area ($x^{-6}in^2$)	Pit Depth (x 10^{-4} in)
1	5	79	18.05	0.762
2	5	79	49.20	1.476
3	5	79	38.40	1.738
4	5	79	45.10	2.500
5	5	79	62.60	3.167
6	5	79	134.80	4.048
7	5	79	113.10	6.310
8	10	57	70.10	1.953
9	10	57	70.85	1.953
10	10	57	39.60	2.310
11	10	57	38.20	2.500
12	10	57	41.60	2.500
13	10	57	79.20	2.500
14	10	57	38.20	2.928
15	10	57	75.00	3.309
16	10	57	176.20	3.500
17	10	57	114.50	3.809
18	10	57	159.7	3.977

TABLE II

TABULATED RESULTS

Load - 5300 psi
Slip - 0.0036
Frequency - 79 cpm

Medium - Dry air
Polish - No. 00 Emery Paper

Number of cycles run	Weight loss after 1st pickling (mg) 4 Specimen Average	Weight loss after 2nd pickling (mg) 2 specimen Average	Depth of Damage after 1st pickling (x^{-3} in.)	Area of Damage after 1st pickling (in^2)	Depth of Damage after 2nd pickling ($x\ 10^{-3}$ in.)
10	0.825	1.0	1.60	-	-
20	1.088	-	-	-	-
20	0.800	1.0	-	-	-
30	0.610	-	3.064	0.0356	-
40	0.800	-	2.508	0.0413	-
50	1.150	-	2.104	0.0350	-
75	1.250	-	2.828	0.0425	-
125	1.000	1.20	-	-	2.17
150	1.000	-	2.710	0.0411	-
300	1.725	-	4.393	0.0436	-

TABLE III

TABULATED RESULTS

Load - 5300 psi
Slip - 0.0036 in.
Frequency - 79 cpm

Medium - dry air
Polish - No. 00 Emery Paper
Weight Loss-4 specimen avarage

Number of Cycles run	Weight loss after test (mg)	Weight loss after 1st pickling (mg)	Weight loss after 2nd pickling (mg)	Depth of Damage after 2nd pickling ($x 10^{-3}$ in.)
1	-	0.600	0.750	-
80	0	1.100	1.625	[illegible]
100	0	1.175	1.450	3.04
100	0	1.175	1.450	2.36
100	0	0.925	1.100	-
200	0	0.925	1.600	-
200	0	1.075	1.275	2.83
200	0	0.750	1.450	2.65
300	0	1.375	1.950	2.76
500	0	1.675	1.925	3.18
500	0	1.675	1.925	4.24
1000	0.2	1.725	2.000	3.10
3000	0.3	1.925	2.675	5.95
5000	0.5	2.450	3.200	5.50
10,000	1.1	3.500	4.100	7.08

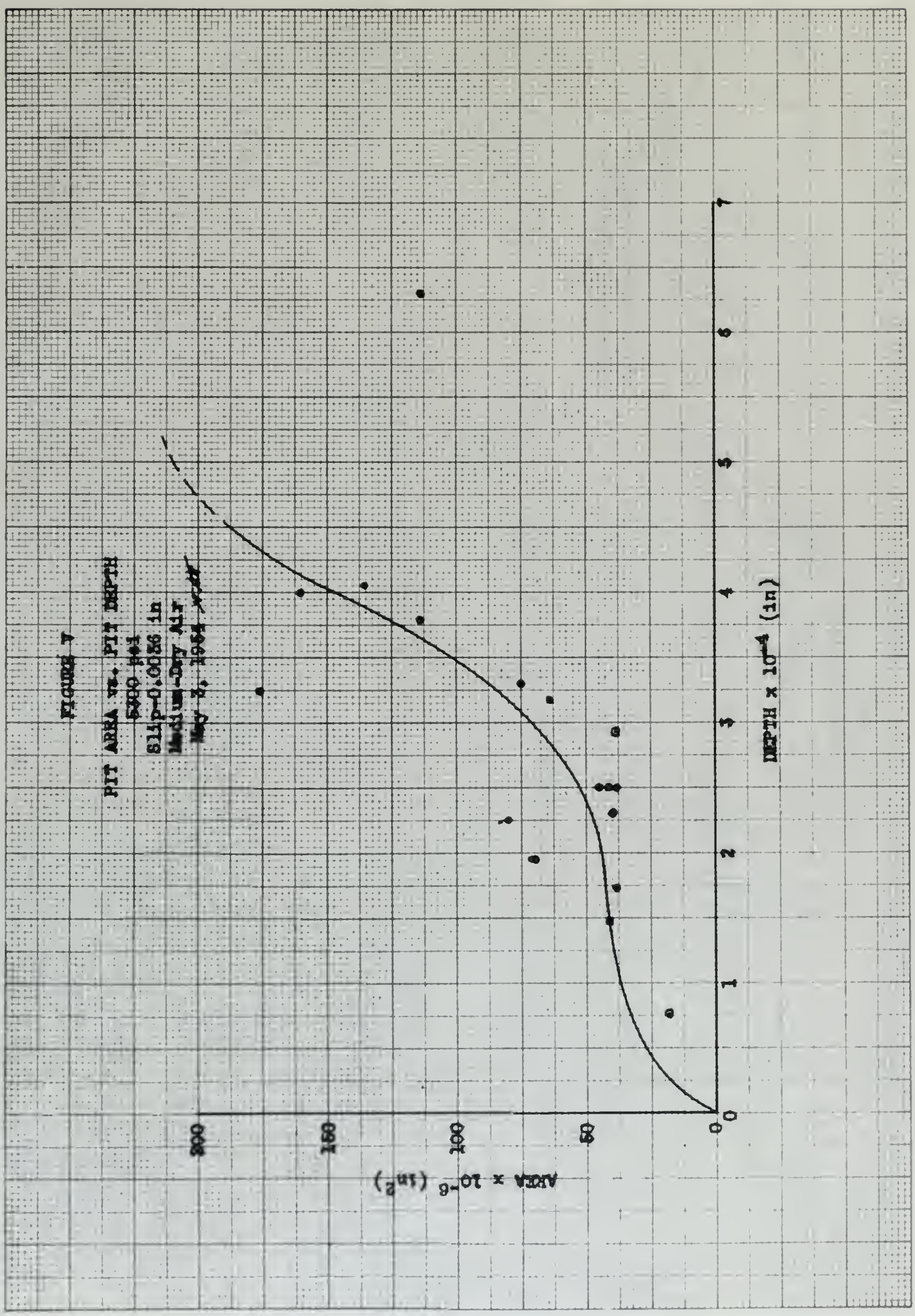
FIGURE V
PIT AREA vs. PIT DEPTH
5300 psi
Slip-0.0036 in
Medium-Dry Air
May 8, 1964
AREA x 10^-6 (in^2)
0
50
100
150
200
DEPTH x 10^-4 (in)
0
1
2
3
4
5
6
7

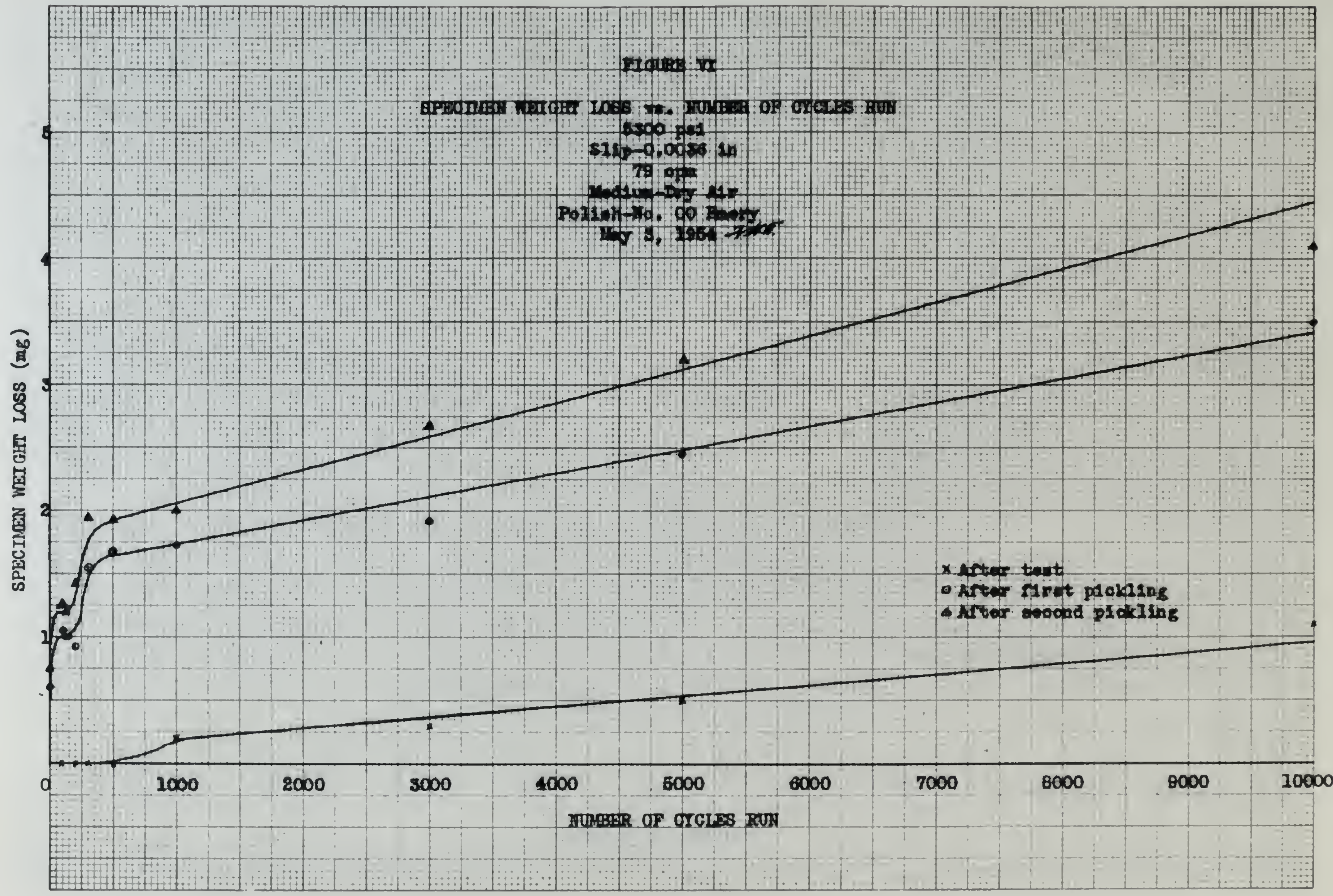

FIGURE VI

SPECIMEN WEIGHT LOSS vs. NUMBER OF CYCLES RUN
5300 psi
Slip-0.0036 in
79 cpm
Medium-Dry Air
Polish-No. 00 Emery
May 5, 1954

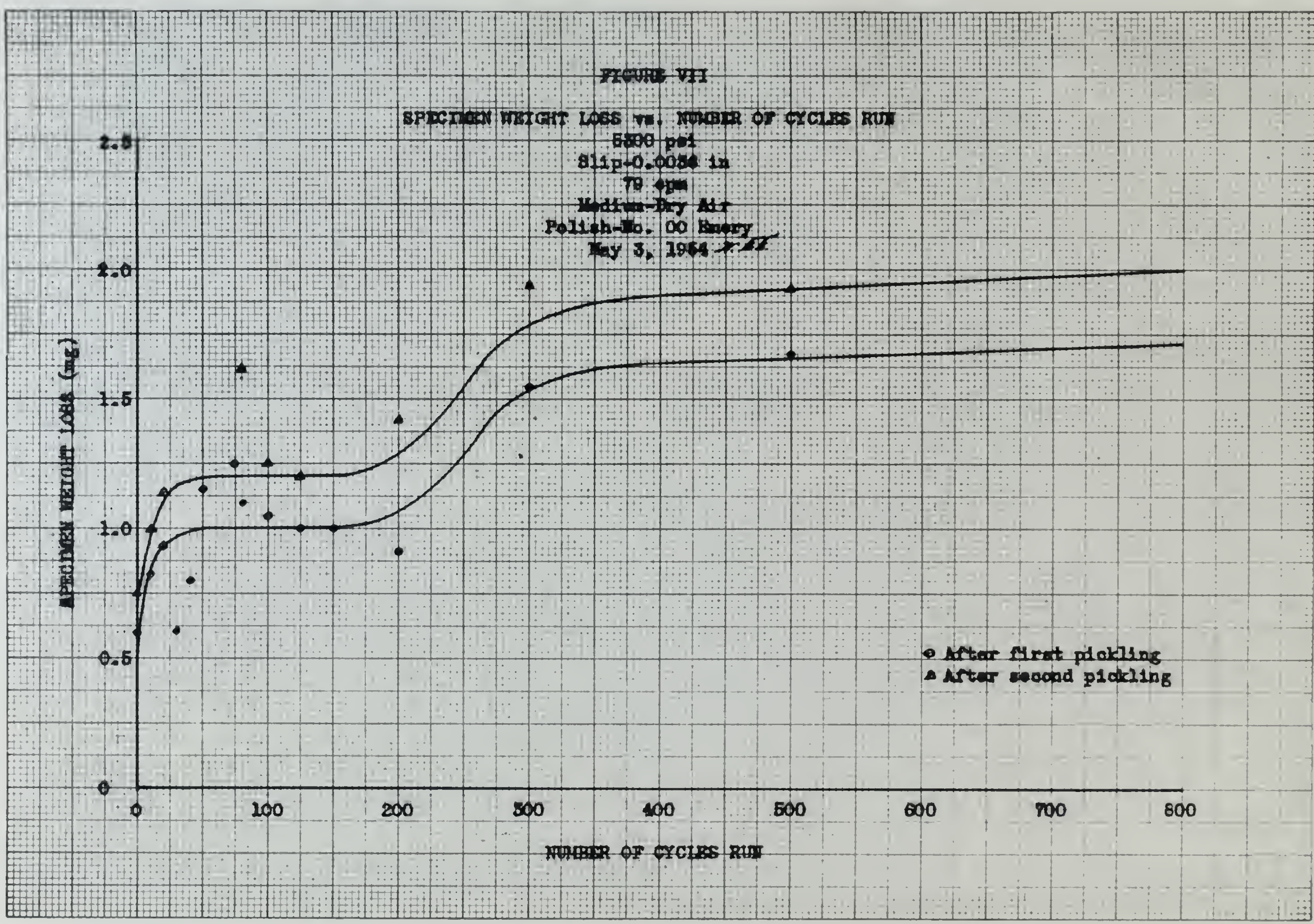
FIGURE VII
SPECIMEN WEIGHT LOSS vs. NUMBER OF CYCLES RUN
5300 psi
Slip-0.0038 in
79 cpm
Medium-Dry Air
Polish-No. 00 Emery
May 3, 1964
SPECIMEN WEIGHT LOSS (mg)
2.5
2.0
1.5
1.0
0.5
0
0
100
200
300
400
500
600
700
800
NUMBER OF CYCLES RUN
After first pickling
After second pickling

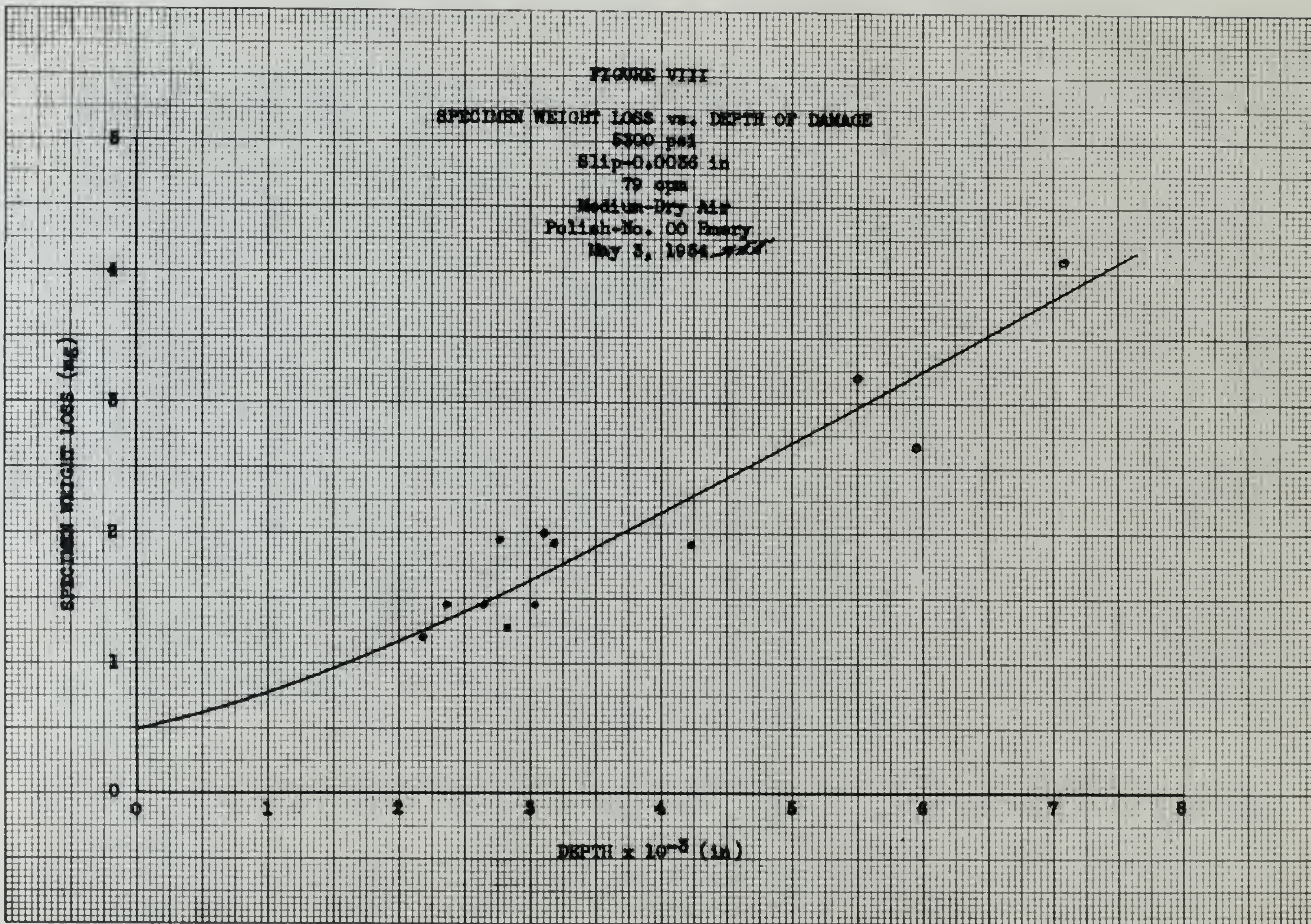

FIGURE VIII

SPECIMEN WEIGHT LOSS vs. DEPTH OF DAMAGE
5300 psi
Slip-0.0036 in
79 cpm
Medium-Dry Air
Polish-No. 00 Emery
May 3, 1954

IV DISCUSSION OF RESULTS

During the investigation of pit growth, it was found that individual pits could be easily identified in the neighborhood of ten cycles. In attempting to measure the area of the individual pits, however, it was found that a random surface polish with No. 1 emery paper was not satisfactory. When a pit was photographed under the microscope, the scratches left in the surface by this polish were so large and random that the boundary of the pit could not be determined with any degree of accuracy. When the surface was given a unidirectional polish with No.000 or No. 0000 emery paper, the scratches left in the surface were considerably smaller. Since these scratches were unidirectional, the boundary of any pit running slightly off the direction of polish could be accurately determined.

It was found that any attempt to use individual pit areas or depths as a substitute for weight loss was impractical. This is due mainly to the fact that in order to distinguish a pit as a single pit, the pit must be so small that the area and depth of all pits so selected fall in the same range of values.

That the above is true may be seen from an analysis of Figure V. When two clean surfaces begin to fret, the sheared off high spots begin to form an area of damage with essentially no depth. Thus we see that in Figure V the area increases faster than the depth. The depth then begins to increase faster than the area. It is suspected that this is due to the abrasive action of the loose wear particles,

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That the above is true may be seen from an analysis of Figure V. When two clean surfaces begin to fret, the smeared off high spots begin to form an area of damage with essentially no depth. Thus we see that in Figure V the area increases faster than the depth. The depth then begins to increase faster than the area. It is suspected that this is due to the abrasive action of the loose wear particles,

limited by the samll amplitude of the relative motion of the specimens. The pit will eventually reach a size such that it will join with the adjacent pit forming a new pit of increased area but with a depth essentially the same as that of the old pit. Thus the area of what is still a single pit, begins to increase faster than the depth. This process continues, the pits increasing in size, until very shortly a single band of damage is formed on the specimen. It is for this reason that "individual" pit areas and depths begin to fall in the same range of values. It is further felt that the process just described will cause the curve of Figure V to continue to increase in a stepwise fashion until such time as the area of damage becomes such that it will remain essentially constant, and the depth of damage will continue to increase. This theory appears to be borne out by the data on the total area of damage given in Table II. The areas over the range from 30 to 300 cycles appear to be essentially constant which would indicate that this particular range is over a flat step in the curve.

In Figure VI, the curve of specimen weight loss after test and before pickling serves no real purpose. Above about 500 cycles the values are inaccurate due to the fact that a certain amount of the debris remains on the specimen and some falls off. In either case, the amount is unknown and thus the value recorded is not a true measure of specimen weight loss. This portion of the curve can serve only to indicate that specimen weight loss increases with the

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number of cycles run. Below about 500 cycles, the recorded weight loss was zero, but it is felt that this is not actually the case. It is felt that if the weight loss could be measured fine enough, the initial portion of this curve would have a shape similar to that of the curves after pickling.

It may readily be seen from an examination of the curves of weight loss after first and second pickling, that the weight loss due to pickling is not a constant. It is thought that this is caused by two factors. First, the plastically deformed material is attacked more readily than the material that has not been plastically deformed. Secondly, the first pickling does not remove either all the plastically deformed material or all the debris. This is substantiated by the findings of Feng and Uhlig (8). Their investigations showed that the loss of weight for clean, untested specimens was about 0.3 milligrams per specimen. An investigation should be made to determine a means of finding the true weight loss of the specimens.

The curves of Figure VII are enlargements of the initial portions of the curves of Figure VI. An analysis of their shape not only substantiates the initial proposal of this investigation, but also the basic mechanism of fretting. The early portion of these curves resembles ordinary wear curves. The shearing off of the contacting high spots produces loose wear particles which do not oxidize immediately. These loose wear particles remain relatively soft and

the abrasive action caused by them is not too great. The original loading is rather poor, being distributed over a relatively small number of contacting high spots. A better distribution of loading takes place through the wear process itself. These two factors combine to cause a leveling off of the rate of wear, and a tendency to arrive at a steady state value.

The loose wear particles tend to be trapped in the hollows of the small-scale waviness of the surface, due to the small amplitude of relative motion. These loose wear particles now begin to oxidize, forming the hard oxide Fe_2O_3. The accumulation of oxide particles quickly fills the space among the high spots. An entire group of high spots thus unites into a single area. These united areas will develop into large pits as the process continues. The rate of weight loss thus increases sharply during this period, as the abrasive action is very effective when the layer of oxide particles is thin. The abrasive action itself will tend to thicken the layer of oxides and thus the rate of weight loss will begin to decrease as time increases. The oxide particles eventually escape into the depressed regions associated with the large-scale waviness of the surface. This eventually leads to a thickening of the layer of oxide particles over the entire area. As the oxide layer becomes thicker and thicker, further increase in the thickness has less effect on decreasing the abrasive action and the rate of weight loss thus tends to reach a steady state.

The foregoing analysis was roughly substantiated by optical observations. After a run of 500 cycles duration, the reddish oxide could just be seen with the naked eye and was quite visible under the microscope. In the vicinity of 200 cycles, some reddish oxides were just visible under the microscope. Examination of the specimens run for about 50 cycles showed no trace of oxides. These observations tend to check the analysis of the shape of the curve.

It is felt that the results presented in Figures VI and VII should only be treated in a qualitative way. The data presented is rather limited in amount and somewhat random in nature to be considered quantitatively. This data should be substantiated by further experiments. If the present test machine were altered to produce frequencies in the neighborhood of ten cycles per minute, it should be possible to obtain a much better quantitative result. It would also be beneficial if a finer balance were used for measuring the specimen weight loss. Additional tests should also be made in the range a little above 10,000 cycles, and the entire range repeated in different atmospheres.

Figure VIII presents a curve of specimen weight loss versus the depth of damage. The data for this curve is inadequate to determine any exact relationship between weight loss and depth of damage. The curve does indicate, however, that the depth of damage should be able to be used as a substitute for weight loss in the measurement

of fretting damage. From this data and the preceding discussion of area measurements, it is felt that any attempt to use area as a measure of fretting damage is impractical. It is recommended that investigations be conducted over a wide range of cycles and in different atmospheres; and the relationship between specimen weight loss and the depth of fretting damage be firmly established.

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V CONCLUSIONS

The significant conclusions drawn from this investigation are as follows:

1. A unidirectional surface polish with No. 000 emery paper is satisfactory for measuring the area and depths of individual pits.
2. A unidirectional surface polish with No. 00 emery paper is satisfactory for measuring the depth of fretting damage.
3. The use of any area measurements or the depth of individual pits as a substitute for weight loss is impractical.
4. The specimen weight loss due to pickling is not a constant but is a function of the amount of fretting damage.
5. The curve of specimen weight loss versus the number of cycles run is initially concave downward. The curve then becomes concave upward followed by a downward curvature leading to a steady rate of weight loss.
6. The depth of fretting damage may be used as a substitute for weight loss in measuring fretting damage.

VI RECOMMENDATIONS

The following recommendations for future work are made:

1. An investigation should be made to determine a method for finding the true weight loss of the specimens.

2. Additional tests should be made in dry air plus other atmospheres, to substantiate quantitatively the shape of the curve of fretting weight loss.

3. Tests should be run at a frequency in the neighborhood of 1 to 10 cycles per minute to quantitatively determine the very early portion of the curve of fretting weight loss.

4. Investigations should be conducted over a wide range of cycles and in different atmospheres to determine the quantitative relationship between the depth of fretting damage and specimen weight loss.

VII APPENDIX

APPENDIX A

SUPPLEMENTARY INTRODUCTION

SUPPLEMENTARY INTRODUCTION

DESCRIPTION OF APPARATUS

The fretting test machine used for this investigation is shown in Figures I, II, and III. The machine was designed by H. H. Uhlig, W. D. Tierney, and A. McClellan and is described in detail in Reference (8).

The machine was designed to produce fretting damage by oscillatory motion of two pairs of test specimens held in place by two moving and two stationary chucks. The chucks allow the tangs of the specimens to fit into a clearance slot. Opposing pairs of set screws in the clearance slot of each chuck, acting against thin shims, clamp the tang perpendicular to the axis of the specimen. The shoulder of each specimen is seated against sheet nylon cemented to the chuck to avoid fretting at this area. The two moving chucks are shrunk on square milled sections at opposite ends of a square shaft. This shrink fit provides a positive joint and minimizes fretting in this area of the machine. The square rocker-arm shaft, which carries the moving chuck, is pinned and bolted to eight leaf springs. These leaf springs form two co-axial crosses, which are bolted and pinned at their extremities to a square cage. The leaf springs thus provide a bearing which will allow small torsional oscillations but which is extremely stiff with respect to any lateral motion.

EXPERIMENTAL INVESTIGATION

DESCRIPTION OF APPARATUS

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An I-beam of aluminium is shrunk on the rocker arm shaft at its midpoint, and is the member through which the motion is applied to the shaft. One end of the rocker arm goes to a cam drive and the other end to a coil spring used to keep the rocker arm in contact with the cam. A variable eccentric in which rotation of the sleeve relative to the shaft changes the eccentricity is used to vary the amount of relative motion between the specimen pairs. The drive shaft is connected to a three-phase, one horsepower motor, operating at 1800 rpm, by a system of V-belt pulleys which allows tests to be conducted at a number of different frequencies.

The normal load between the fixed and moving specimens is applied by pneumatic pistons actuated by high pressure nitrogen. The pistons have hardened spherical ends which bear on hardened plates pinned to the back of end-bell diaphrams in order to transmit the load through the fixed chuck and fixed specimen to the test surface.

To conduct tests in other than laboratory air, two split rectangular cells are provided. Each cell is clamped over a mated pair of specimens and the desired environment is then introduced to the cell. A glass window bolted and cemented to the top of the cell allows observation of the specimens during test.

The standard test specimen (shown in Figure IV) is cut from SAE 1080 cold-finished steel. The specimen is one inch in diameter and one inch long. One end of the specimen is counterbored 7/8 inch

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The normal load between the fixed and moving specimens is applied by pneumatic pistons actuated by high pressure nitrogen. The pistons have hardened spherical ends which bear on hardened plates pinned to the back of end-ball diaphragms in order to transmit the load through the fixed chuck and fixed specimen to the test surface.

To conduct tests in other than laboratory air, two split rectangular cells are provided. Each cell is clamped over a mated pair of specimens and the desired environment is then introduced to the cell. A glass window bolted and cemented to the top of the cell allows observation of the specimens during test.

The standard test specimen (shown in Figure 17) is cut from SAE 1020 cold-finished steel. The specimen is one inch in diameter and one inch long. One end of the specimen is counterbored 7/8 inch

in diameter by 1/16 inch deep, forming and annular test surface of 0.184 square inch at a mean radius of 0.438 inch. The opposite end of the specimen is cut away to form a centered square tang 5/16 inch long. In test, the specimens are pressed together with the annular surfaces in contact. A jig is used to align the specimens concentrically with each other and with respect to the shaft of the moving chunks.

APPENDIX B

DETAILS OF PROCEDURE

DETAILS OF PROCEDURE

All of the tests were run under a standard set of test conditions, varying only the number of cycles that the tests were run. The test conditions were selected after a study of reference (8), and were so chosen that a substantial amount of damage would be caused in a fairly short interval of time. The standard conditions selected were, a normal loading of 5300 psi, a relative slip of 0.0036 inch and a frequency of alternation of 79 cycles per minute. The atmosphere chosen was dry air at room temperature.

Having selected the test conditions, several tests were first made to determine an approximate number of cycles at which the fretting damage was significant yet such that it was possible to identify individual damage pits. The surface of specimens for these tests was given a random polish with No. 1 emery paper.

A test was then run for 10.5 cycles using specimens having a random surface polish with No. 1 emery paper. Prior to final polishing, the surfaces of all the specimens were given three diamond indentations spaced approximately 120 degrees apart. These diamond indentations were made using a Vickers Hardness Test machine and a diamond indentor having a major axis ratio of 35 to 1 and a minor axis ratio of 6 to 1. The loading used on the Vickers machine was 20 kilograms. Upon completion of the test, several individual pits were selected at random from one specimen and photographs taken of them using a magnification of 120X. A photograph of one of the diamond indentations was also

taken using the same magnification. The specimen was carefully dressed down by hand, using No. 000 and No. 0000 emery paper, until each pit under observation just disappeared. As each pit disappeared, a photograph was again taken of the same diamond indentation. The area of each pit was measured from the photograph using a planimeter. The depth of each pit was determined by the difference in the successive indentation photographs using the trigonometric relationships for a right triangle.

A test was run for 5 cycles duration at a frequency of 79 cycles per minute. The surface preparation was a unidirectional polish with No. 0000 emery paper. Another test was run for 10 cycles at a frequency of 57 cycles per minute. The surface preparation for this test was a unidirectional polish with No. 000 emery paper. Four to six individual pits were selected from each of two specimens and the area and depth of each pit was determined as set forth in the preceding paragraph. These tests were run at different frequencies and with different surface finishes because it was felt that the pit growth should depend only on the length of time that the pit was allowed to grow.

A number of runs were made varying the duration of test from 10 to 300 cycles. The surface preparation of the specimens for these tests was a unidirectional polish with No. 00 emery paper. All specimens were weighed before testing and were pickled and weighed after testing. One specimen from each of six tests was selected and a photograph taken

of the entire fretted surface. The photographs were enlarged until the specimen was 10 times its original size. The entire area of damage was then measured using a planimeter. The deepest depth of damage was then measured, the specimen being dressed down until all damage just disappeared. The technique for measuring depths was the same as that used before except that the standard Vickers diamond indentor was used with a 40 kilogram load. The standard indentor was used since it was felt that the depths would be too great for the previously used indentor.

A second series of tests was made varying the duration of test from 1 to 10,000 cycles. The specimen surface preparation for these tests was again a unidirectional polish with No. 00 emery paper. The specimens were again weighed before testing. Upon completion of the test, the specimens were rinsed in boiling benzene, dried and weighed. The specimens were then pickled and weighed again. All specimens were then given a second pickling and reweighed. After the second pickling, one or two specimens from each test were given a diamond indentation with the standard Vickers indentor using a load of 40 kilograms. The small ridge formed around the indentation was carefully dressed off and the deepest depth of damage to the specimen then determined as previously outlined for the preceding tests.

of the entire flexed surface. The photographs were enlarged until the specimen was 10 times its original size. The entire area of damage was then measured using a planimeter. The deepest depth of damage was then measured, the specimen being dressed down until all damage just disappeared. The technique for measuring depths was the same as that used before except that the standard Vicker's diamond indenter was used with a 10 kilogram load. The standard indenter was used since it was felt that the depths would be too great for the previously used indenter.

A second series of tests was made varying the duration of test from 1 to 16,000 cycles. The specimen surface preparation for these tests was a wet sand-longitudinal polish with No. 00 emery paper. The specimens were again weighed before testing. Upon completion of the test, the specimens were placed in boiling benzene, dried and weighed. The specimens were then pickled and weighed again. All specimens were then given a second pickling and reweighed. After the second pickling, one or two specimens from each test were given a diamond indentation with the standard Vickers indenter using a load of 10 kilograms. The small ridge formed around the indentation was carefully dressed off and the deepest depth of damage to the specimen then determined as previously outlined for the preceding tests.

PREPARATION AND CLEANING OF SPECIMENS

The test specimens were given the desired surface finish by hand polishing on emery paper, using a polishing guide to maintain a flat surface. The specimens were then cleaned in acetone and weighed. The specimens were then clamped firmly in the test machine and the full test procedure applied.

When the test was completed the specimens were degreased in hot benzene. Depending upon the particular test under study, the specimens were then weighed, or pickled and weighed after pickling. The pickling procedure was carried out as follows:

1. The specimen was immersed for 30 seconds in a pickling solution heated to 50°C (120°F). The pickling solution is 5% by weight sulfuric acid and 0.1% by weight of quinolinethiodide, a pickling inhibitor.
2. The specimen, held in tongs, was taken from the pickle solution and placed under running water.
3. The fretted surface of the specimen was then scrubbed with a stiff bristle brush and rinsed again in running water.
4. The specimen was then rinsed in hot acetone followed by a rinse in boiling distilled benzene.
5. The dried specimen was placed in a desiccator and left for at least one hour to allow thermal equilibrium to be attained.
6. Each specimen was then weighed and the weight recorded.

APPENDIX C

SUPPLEMENTARY DISCUSSION

SUPPLEMENTARY DISCUSSION

The diameters of the specimen faces were accurate to 0.0005 inch. With careful hand polishing on a flat glass or steel plate, the error in the surface flatness of the specimens was negligible.

The pressure at the interface of the specimens is estimated to be within $\pm$ 30 psi. Even with an accurate pressure gauge there is an error. If the faces of the two specimens do not meet exactly parallel and together with no pressure applied, a small amount of pressure is necessary to bring them into contact when the test begins.

The frequency of alternation was checked periodically and was accurate to within $\pm$ 1 cpm. The total number of cycles run, measured with a counter attached to the eccentric shaft, was estimated to be accurate to within $\pm$ 5 cycles in 10,000 cycles.

The specimen weight loss was measured with an analytical balance that read to 0.1 milligram. It is felt that the accuracy here is in question, particularly in the regions of small weight loss. It is recommended that each specimen be weighed twice, each time by a different person.

It is estimated that the error involved in pickling is negligible. This is particularly true if all pickling is done by the same person and is done in exactly the same manner each time.

There are errors involved in the measurement of the depth of damage. If the two specimens do not meet exactly parallel, the pressure is not the same over the entire surface of contact. Since the depth measured is the deepest found, this difference in pressure will introduce errors in the measurement. The diamond indentations may also introduce errors if they are not exactly correct. It is felt, however, that with the standard Vickers indentor this error is usually negligible. There is also an error introduced in the measurement of depth due to an inaccuracy in determining when the damage just disappears. If the dressing down is done by hand, and all observations are made under a microscope, it is felt that this error may be reduced to the point where it will also be negligible.

ANALYSIS OF SPECIMEN STOCK

The certified mill analysis of the SAE 1018 cold-finished steel used in the specimens is as follows:

Carbon, percent	0.15
Manganese, percent	0.75
Phosphorus, percent	0.008
Sulphur, percent	0.027

A check analysis made by the Department of Metallurgy indicated a carbon content of 0.16 percent.

APPENDIX D

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LITERATURE CITATIONS

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Thesis
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